ENGIN STORAGE

UNIVERSITY OF ILLINOIS BULLETIN
Issued Weekly
Vol. XXIII August 17, 1926 No. 50
[Entered as second-class matter December 11, 1912, at the post office at Urbana, Illinois, under the Act of August 24, 1912. Acceptance for mailing at the special rate of postage provided for in section 1103, Act of October 3, 1917, authorized July 31, 1918.]

THE
MEASUREMENT OF THE PERMEABILITY OF CERAMIC BODIES

BY

PIERCE W. KETCHUM
ALBERT E. R. WESTMAN
RALPH K. HURSH

LIBRARY
OCT 6 1927
UNIVERSITY OF ILLINOIS

CIRCULAR NO. 14
ENGINEERING EXPERIMENT STATION

Published by the University of Illinois, Urbana

Price: Fifteen Cents

THE Engineering Experiment Station was established by act of the Board of Trustees of the University of Illinois on December 8, 1903. It is the purpose of the Station to conduct investigations and make studies of importance to the engineering, manufacturing, railway, mining, and other industrial interests of the State.

The management of the Engineering Experiment Station is vested in an Executive Staff composed of the Director and his Assistant, the Heads of the several Departments in the College of Engineering, and the Professor of Industrial Chemistry. This Staff is responsible for the establishment of general policies governing the work of the Station, including the approval of material for publication. All members of the teaching staff of the College are encouraged to engage in scientific research, either directly or in coöperation with the Research Corps composed of full-time research assistants, research graduate assistants, and special investigators.

To render the results of its scientific investigations available to the public, the Engineering Experiment Station publishes and distributes a series of bulletins. Occasionally it publishes circulars of timely interest, presenting information of importance, compiled from various sources which may not readily be accessible to the clientele of the Station.

The volume and number at the top of the front cover page are merely arbitrary numbers and refer to the general publications of the University *Either above the title or below the seal* is given the number of the Engineering Experiment Station bulletin or circular which should be used in referring to these publications.

For copies of bulletins or circulars or for other information address

THE ENGINEERING EXPERIMENT STATION,
UNIVERSITY OF ILLINOIS,
URBANA, ILLINOIS

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

CIRCULAR NO. 14 AUGUST, 1926

THE MEASUREMENT OF THE PERMEABILITY OF CERAMIC BODIES

BY

PIERCE W. KETCHUM
RESEARCH GRADUATE ASSISTANT IN CERAMIC ENGINEERING

ALBERT E. R. WESTMAN
RESEARCH ASSOCIATE IN CERAMIC ENGINEERING

AND

RALPH K. HURSH
ASSOCIATE PROFESSOR OF CERAMIC ENGINEERING

ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

UNIVERSITY
of ILLINOIS
PRESS

CONTENTS

PAGE

I. GENERAL INTRODUCTION 5

1. Definition of Permeability 5
2. Importance of Permeability Measurements 5
3. Work of Previous Investigators 5
4. General Principles of Permeameter Design 6
5. Purpose of this Circular 7
6. Acknowledgement 8

II. TYPE A PERMEAMETER FOR EXTREMELY DENSE BODIES . . . 8

7. General Features 8
8. Range of Usefulness 8
9. Standard Pressure Adopted 8
10. Description of Permeameter 8
11. Calibration 10
12. Operation 10
13. Calculation of Results 11
14. Precautions 12
15. Possible Modifications to Increase Range 12

III. TYPE B PERMEAMETER FOR FULL-SIZED BRICKS 13

16. General Features 13
17. Principles Involved 13
18. Standard Pressure Adopted 13
19. Range of Usefulness 14
20. Description of Permeameter 14
21. Calibration 17
22. Operation 18
23. Calculation of Results 18
24. Precautions 19
25. Modifications of Apparatus 19

APPENDIX A 22

1. The Permeability of Typical Ceramic Bodies . . . 22
2. Suggested Uses for Permeability Measurements . . 22
3. The Use of the Type A Permeameter as a Porosimeter 25

Digitized by the Internet Archive
in 2011 with funding from
University of Toronto

http://www.archive.org/details/bulletinu14univ

THE MEASUREMENT OF THE PERMEABILITY OF CERAMIC BODIES

I. INTRODUCTION

1. *Definition of Permeability.*—The permeability of a body is the property of permitting the passage of fluids. It is measured by determining the rate at which some standard fluid, generally water or air, flows through a specimen of known dimensions, under a definite fluid pressure head.

Permeability is often confused with porosity, which is measured by the ratio between the volume of the pores in a body and the total volume of the body itself, and, unlike permeability, has no direct connection with the *flow* of fluids. Permeability, which might be called fluid conductivity, and porosity, which might be called fluid capacity, are distinct properties of a material just as thermal conductivity and thermal capacity are distinct. It is not surprising, therefore, that bodies of equal porosity frequently differ greatly in permeability.

2. *Importance of Permeability Measurements.*—Of two bodies having equal porosities, the one having the larger pore sizes will, in general, have the greater permeability. It is thus possible, by means of permeability measurements, to obtain a more precise idea of the structure of a body than is afforded by porosity measurements alone. The permeability of a body is also very much more affected by changes in structure than is its porosity. Permeability measurements, therefore, provide a means of obtaining an intimate knowledge of the changes in the structure of a body which occur when it is subjected to such important processes as drying and burning.

As the structure of a body is an important factor in its drying behavior, its behavior with respect to oxidation, and its resistance, when burned, to slagging and spalling, the importance of the information afforded by permeability measurements is quite evident. Some of the ways in which such measurements can be used to advantage in ceramic investigations are indicated in the appendix to this discussion.

3. *Work of Previous Investigators.*—While the value of permeability measurements has not been fully realized in the past, studies of the permeability of various materials have been made from time to time.

King and Slichter* carried out very exhaustive studies of the movements of ground waters, in which measurements of the permeability, to both water and air, of a great variety of packed aggregates were made.

Wologdine† made permeability, porosity, and thermal conductivity measurements on many ceramic materials. In his apparatus, the air displaced by water entering a cylinder at a constant rate escaped through a small specimen sealed in a glass tube by means of paraffin. The rate of air displacement which caused a pressure drop of 1 cm. of water across the specimen was used as a measure of its permeability.

Searle‡ describes two simple permeameters in which water is used as a standard fluid.

The American Foundrymen's Association§ has experimented with different types of permeameters for determining the permeability of molding sands. In the apparatus finally adopted, air from a calibrated gasometer flows through the specimen; the rate of air flow is ascertained by determining the rate of fall of the bell of the gasometer, and the pressure drop across the specimen is measured by a liquid pressure gauge.

Kessler¶ has recently published the results of permeability measurements of building stones of various kinds, using water as the fluid and pressures up to 300 lb. per sq. in. (21 kg. per sq. cm.)

4. *General Principles of Permeameter Design.*—Experimental studies have shown that there are certain factors in the design of permeameters for ceramic bodies which cannot be neglected if significant results are to be secured.

For all unburned ceramic bodies and for many burned bodies, air, rather than water, must be used as the standard fluid, as contact with water changes their physical properties materially. With dense bodies, also, air is a more convenient fluid to use as such bodies are more permeable to air than to water.

Equilibrium of flow must be secured during a measurement. An appreciable amount of time is required to attain a steady rate of flow through a specimen after a definite difference of pressure on the two sides has been established. Equilibrium is attained when the rate of flow due to the given pressure difference becomes constant.

---

*Nineteenth Annual Report, U. S. Geological Survey, Part II, 1899.

†Electrochem. and Metallurg. Industry, VII, pp. 383-389 and pp. 433-436, 1909. Trans. by Queneau.

‡Searle, Alfred B., "The Chemistry and Physics of Clays and Other Ceramic Materials," Ernest Been, Ltd. London, 1924.

§Trans. Amer. Foundrymen's Assoc. XXXI, pp. 708-721, 1924.

¶Technologic Papers of the Bureau of Standards, No. 305, Jan., 1926.

It is necessary, in most cases, to decide on a standard pressure difference and standard dimensions for the specimens if strictly comparable results are to be obtained. This is due to the fact that the permeability of a body is not necessarily a constant, and measurements made with different pressures may give different values.*

It is also impossible, unless a great deal of experimental work has been performed, to calculate, with any accuracy, the permeability of a given specimen from that of another specimen of the same material but of different dimensions. This is due to the fact that, for most materials, the permeability is not a simple function of the dimensions of the specimens. The practice of expressing permeabilities in terms of unit cubes and unit pressure differences, when the actual measurements were made at different pressures and with specimens of different dimensions, is apt to give very misleading results.

With raw clay bodies and bodies that have been burned to a temperature below the dehydration point of the clay, moisture conditions must be controlled because of the hygroscopic properties of such bodies. With well burned bodies this effect is negligible.

The rate of air flow through a body depends on the viscosity of the air, which is in turn affected by changes in its moisture content and temperature. Under ordinary laboratory conditions these changes are not large enough to cause appreciable errors.

5. *Purpose of this Circular.*—It is the purpose of this circular to describe two types of permeameters, called types A and B for convenience, which have been developed in connection with investigations of the drying behavior of porcelain bodies, the burning behavior of different kinds of brick, and the problems involved in the utilization of refractories in water-gas sets and boiler settings.

In both cases, these represent radical departures from previous types of permeameters, and are the result of considerable experimental work, which was undertaken when it was found that the usual types of permeameter were not suited to the measurements of ceramic bodies.

Type A permeameter is used in measuring the permeability of small specimens of extremely dense bodies. Type B permeameter is used in measuring the permeability of standard-sized, burned refrac-

---

*King and Slichter, *loc. cit.*

tories; a modification of this type, which will be described, is used for full-sized unburned clay brick.

6. *Acknowledgment.*—The authors wish to express their appreciation of the interest and help of Professor C. W. Parmelee, Head of the Department of Ceramic Engineering.

II. Type A Permeameter for Extremely Dense Bodies

By Pierce W. Ketchum

7. *General Features.*—Type A permeameter was developed for the purpose of measuring the permeabilities of small specimens of raw clays, and of burned and unburned porcelain bodies, so as to study the effect of drying and burning on their internal pore structures.

This permeameter is of the suction type, that is, air from the room is drawn through the specimen by maintaining a constant standard reduced pressure within the apparatus by means of an adjustable mercury column. The rate of air flow under this pressure difference is measured by what is essentially a gas measuring tube.

8. *Range of Usefulness.*—Type A permeameter was designed primarily for very dense bodies. Specimens about 5 mm. thick of unburned ball clays which have been cast or pressed from thoroughly blunged slip, or of porcelain bodies burned a few cones below complete vitrification, have permeabilities of a magnitude most easily measured by this instrument.

9. *Standard Pressure Adopted.*—To avoid extrapolation on the permeability-pressure and permeability-thickness relations (these relations also being likely to vary with different bodies), the permeability was always measured under a convenient standard pressure, namely, that corresponding to 20 cm. of mercury, and the specimens were all made about 5 mm. thick. The results were expressed in cubic centimeters of air per minute, measured at a pressure corresponding to 560 mm. of mercury, flowing through one square centimeter of a specimen 5 mm. thick under a pressure difference of 20 cm. of mercury.

10. *Description of Permeameter.*—As seen from Figs. 1 and 2, the apparatus consists of a device for sealing in the specimen, a connecting

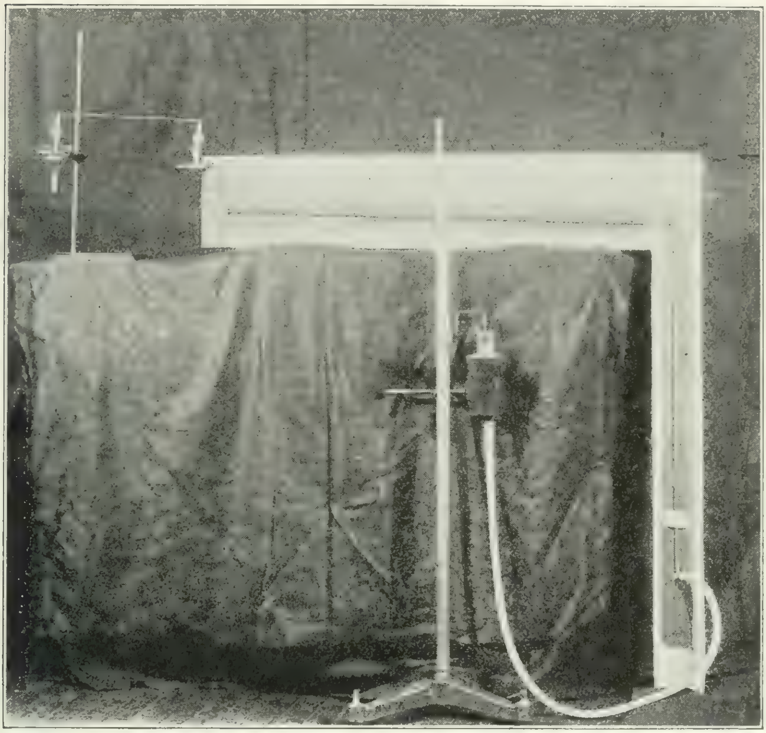

FIG. 1. TYPE A PERMEAMETER

capillary tube C, a three-way stopcock K, and a horizontal capillary measuring tube T, about 1 meter long, sealed to a vertical tube D, of larger bore, which is in turn connected to a mercury reservoir R at least 3 cm. in diameter at the mercury surface, by a heavy rubber tube. The stand M carries a scale with a pointer for measuring the height of the mercury in the reservoir. Finally, an ordinary water aspirator pump is attached at W. All the glass tubing except D has a bore of about 2 mm.

Part B has a shallow flare, expanding to about 2.5 cm. in diameter at the bottom, and is ground on the bottom edge so as to fit closely to the specimen E. The specimen is held in place by a short-necked funnel, which is in turn supported on a ring stand I.

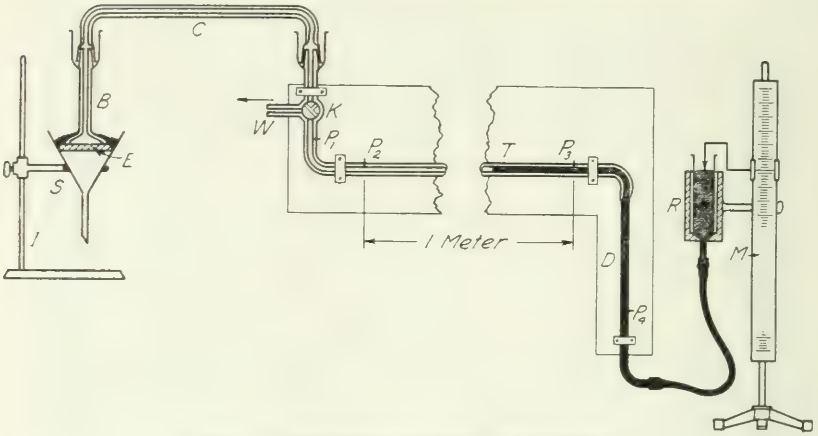

FIG. 2. DIAGRAM OF TYPE A PERMEAMETER

The tube C is connected to B and K by ground joints which are provided with mercury cup seals.

11. *Calibration.*—The pressure across the specimen is determined by the difference in height of the mercury levels in T and in R. In order to obtain a zero point of pressure on the scale, a fixed point, such as P_1, is chosen on the tube. The reservoir is then adjusted to such a height that when the mercury column is drawn up to P_1 and allowed to run back freely, it will come to rest about half way between P_2 and P_3. With the reservoir adjusted in this way, the reading for zero pressure is taken as the height of the mercury in the reservoir when the mercury column stands at P_1.

To obtain the standard pressure difference of 20 cm., the mercury column is maintained at P_1 while the reservoir is lowered until the mercury in it is 20 cm. below the level for zero pressure. Volume v of tube T between P_2 and P_3 is measured by weighing the amount of mercury required to fill this portion of the tube.

12. *Operation.*—Part B is removed from the rest of the apparatus by lowering the ring of the support stand, and sealed to specimen E by means of hot beeswax or other suitable material. This combination is then sealed into place in the funnel which, after being cooled to room temperature, is placed in the ring S and raised so as to connect B and C. A rubber band over S and C prevents the parts from becoming dis-

placed before the vacuum is established. Stopcock K is then turned so as to connect the vacuum pump with both C and T. The pump reduces the pressure in these tubes, thereby causing the mercury column to travel along T from P_2 to P_1. When the column is somewhere near P_1 stopcock K is turned so as to connect only C and T. Due to the passage of air through the specimen, the mercury column will now run back and the time t required for it to go from P_2 to P_1 is measured with a stop-watch.

13. *Calculation of Results.*—Area A of the bottom opening of part B may be taken as the effective area of the piece because measurements have shown that the air flow through the specimen occurs almost entirely along straight lines perpendicular to the surfaces of the piece, as long as the ratio of A to the thickness of the specimen is sufficiently large. For instance, in the present measurements, the diameter of the bottom opening of part B was about five times the thickness of the piece, and the error due to non-linear flow was practically negligible. For higher accuracy, the bottom of the specimen can be waxed so as to expose an area equal and opposite to that exposed above.

It was found by experiment that the time t is directly proportional to the thickness d of the specimen. This relation can also be predicted from theoretical considerations on the assumption that for an infinitesimal element of a capillary tube the velocity of flow is inversely proportional to the length of the element.

The permeability P is therefore given by the expression

$$P = \frac{2vd}{tA}$$

where v is the volume in cc. of the tube T between P_1 and P_2 (see Section 11), d is the thickness of the specimen in cm. (see Section 9), t is the time in minutes required for the mercury column to go from P_2 to P_1, (see Section 12) and A is the area in sq. cm. of the bottom opening of the part B (see Section 13). The factor 2 is required because we have chosen 0.5 cm. as the standard thickness (see Section 9). When the same apparatus is used to measure specimens of equal thickness, time t can be taken as a measure of their relative permeability, v, d, and A being constant. To compare permeabilities measured by different type A instruments all operated at nearly 760 mm. barometric pressure, the values of v, d, and A for the different instruments must be taken into account.

14. *Precautions.*—Considerable difficulty was encountered in obtaining a satisfactory seal between part *B* and the specimen. Due to the relatively high pressure existing across the seal and the low permeabilities of the specimens employed, leaks tended to develop between the specimen and the wax. To prevent this trouble, the wax must be so fluid when applied that it will actually penetrate the specimen slightly.

For unburned bodies a cold seal would be much superior to hot beeswax, on account of the effect of the heat on the moisture content of the specimen, but a satisfactory cold seal has not yet been found. To reduce the errors due to the seal, care was taken to subject each specimen to exactly the same treatment.

Care must also be used in handling the mercury within the apparatus so as to keep it clean. The rubber tube connected to the reservoir should be thoroughly scrubbed on the inside before using. If a scum is allowed to collect on the surface of the mercury column, the mercury will have a tendency to stick in tube *T* so as to give an uneven flow.

In designing a type A permeameter care should be taken to keep the total volume contained within the apparatus between the specimen and the mercury column at a minimum, otherwise fluctuations due to temperature changes become very large and pressure equilibrium is established very slowly. Also, the vertical tube *D* should not be omitted and should be sealed, rather than connected with a rubber tube, to the horizontal tube *T*, since *T* operates under reduced pressure, and a rubber connection tends to allow the entrance of bubbles into the mercury column.

The permeability of unburned specimens is affected very much by slight changes in moisture content, since this moisture reduces the average pore size, and the permeability changes very rapidly with the pore diameter, probably as the fourth power. To prevent changes in the humidity of the air in the room from affecting the results it is therefore necessary to keep the specimens in a desiccator over dilute sulphuric acid. The rapidity with which equilibrium of flow is attained in type A permeameter makes it unnecessary to control the humidity of the air drawn through the specimen, since the measurements can be made before any appreciable change in the moisture content of the specimen has occurred.

15. *Possible Modifications to Increase the Range.*—By using water or other liquid in place of mercury, and by increasing the thick-

ness of the specimen, the upper limit of measureable permeabilities might be increased as much as 250 times.

There is practically no theoretical lower limit of permeabilities which could be measured by type A permeameter if the following modifications were made:

(a) A smaller capillary tube substituted for T
(b) The area of the specimen increased and the thickness decreased
(c) The time of flow, t, lengthened
(d) The pressure within the apparatus decreased

The last method would be especially effective. A change of pressure from 50 cm. to 0.1 mm. of mercury would increase the sensitivity 10,000 times. In such cases, however, leaks would be very troublesome.

III. Type B Permeameter for Full-Sized Bricks

By Albert E. R. Westman and Ralph K. Hursh

16. *General Features.*—Type B permeameter was developed for the purpose of measuring the permeability of commercial refractories, using full-sized bricks (9 in. x 4½ in. x 2½ in. = 23 cm. x 11.4 cm. x 6.4 cm.) as specimens. A modification of this type has been used for measuring full-sized unburned clay brick. Since it is not necessary to seal the specimen to the apparatus with wax or cement, type B permeameter is particularly useful in investigations of refractories, as the same specimens can be used immediately for other tests.

17. *Principles Involved.*—Type B permeameter operates on the continuous flow principle, i. e., a continuous stream of air is maintained through the brick during a determination. The permeability is determined from the volume rate of flow through the thickness, i. e., parallel to the 2½-in. axis of the brick, which corresponds to a standard pressure drop through the brick. This volume rate of flow is measured by means of flowmeters. By maintaining the steady flow of air until the flowmeters give constant readings, one can be sure that equilibrium of flow has been secured. This is an advantage when working with full-sized brick, as they frequently have a large pore volume (300 to 400 cc.) and, consequently, an appreciable time is required to establish the equilibrium pressure gradient through the brick.

18. *Standard Pressure Adopted.*—A pressure drop of 1 cm. head of water, at 4 deg. C., along the 2½-in. axis of the specimen was

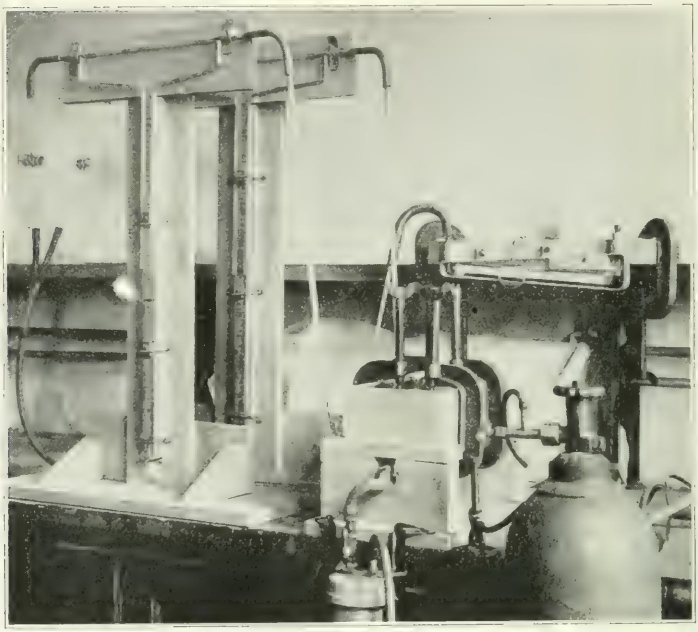

FIG. 3. TYPE B PERMEAMETER

adopted as standard. This corresponds to pressure differences that are apt to occur when the bricks are used in furnaces and to air flow rates that can be measured conveniently.

19. *Range of Usefulness.*—Type B permeameter can be used in measuring the permeability of any of the commercial refractories. By suitable modifications, which will be described later, this range can be greatly extended.

20. *Description of Permeameter.*—As shown in Figs. 3 and 4, respectively, the apparatus consists essentially of a mercury trough and reservoir, two flowmeters (only one of which is shown in the diagram), a small gasometer, and a pressure gauge. The mercury trough and reservoir are used in sealing the brick to the apparatus, the flowmeters in measuring the volume rate of air flow through the brick, and the gasometer and pressure gauge in maintaining the standard pressure drop across the brick.

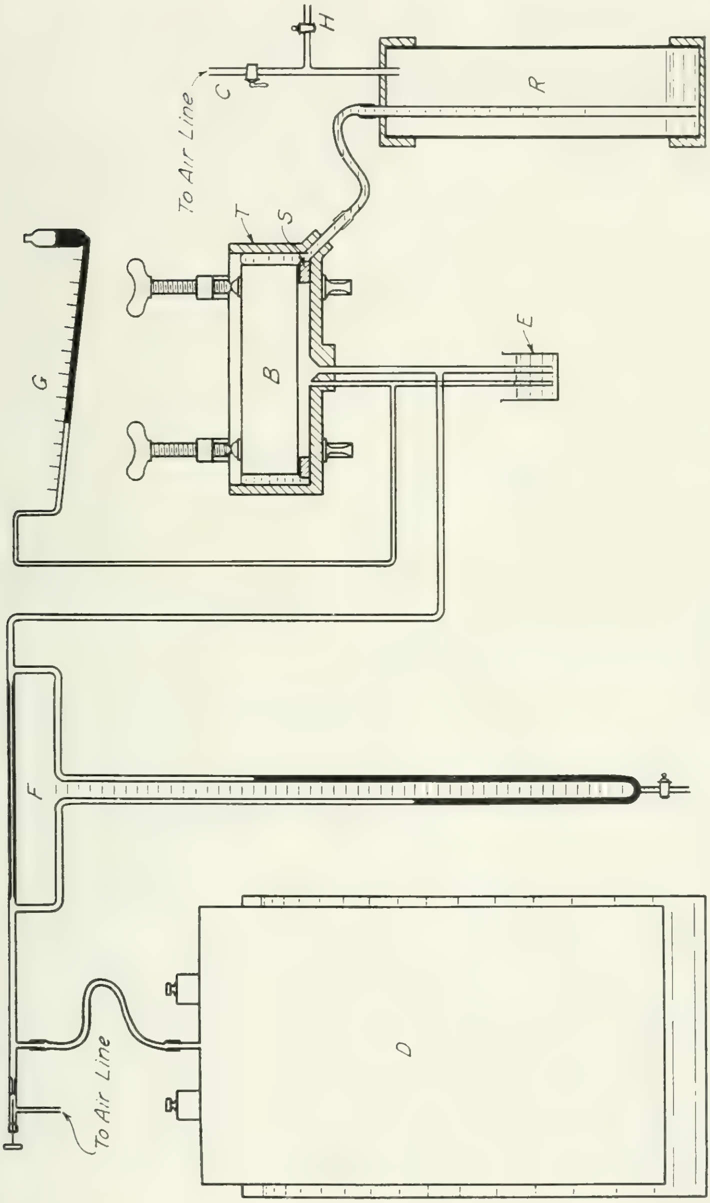

Fig. 4. Diagram of Type B Permeameter

The mercury trough *T* (Fig. 4) consists of a cast-iron box, open at the top, with walls 3/8 in. thick and inside dimensions 3½ in. x 5½ in. x 10 in. (9 cm. x 14 cm. x 25 cm.). In the middle of the bottom of the mercury trough is a cone-shaped depression; a glass tube (inside diameter 6 mm.) leads from the bottom of this depression to the flowmeters, and another glass tube (inside diameter 4 mm.) leads from a point at the side of this depression to the pressure gauge *G*. A soft felt gasket *S* of rectangular shape, ½ in. (13 mm.) thick, with outside dimensions 9 in. x 4½ in. and inside dimensions 7½ in. x 3 in., (19 cm x 7.6 cm.) is glued to the bottom of the mercury trough in such a position that there is ½-in. (13 mm.) clearance between it and the walls of the trough. A 3/8-in. nipple is inserted at the bottom and middle of one end of the trough and is connected by means of a heavy rubber tube to a 3/8-in. iron pipe which reaches almost to the bottom of the mercury reservoir. Reservoir *R* consists of a 20-in. length of 2½-in. iron pipe, which is capped at both ends, and is supported in an upright position just below the mercury trough. By applying air pressure to the reservoir through stopcock *C*, mercury can be forced up into the trough; by closing *C*, the mercury level in the trough can be kept constant; and by releasing the air pressure through *H*, the mercury can be returned to the reservoir.

The flowmeters are made of glass, each flowmeter (see *F*, Fig. 4) consisting of a capillary tube and a manometer, which are sealed together in such a way that the manometer measures the pressure drop across the capillary tube. Ellison gauge oil is used in the manometers. A tap is provided at the bottom of each manometer so that the oil can be removed and replaced easily; about 2 cm. of mercury is kept above the tap to prevent the oil from dissolving the tap grease and leaking out. Scales, 60 cm. long, with millimeter divisions, are used to measure the differences in level of the liquid columns in the manometers. Stopcocks are arranged so that either flowmeter can be used when making a measurement.

Gasometer *D* (Fig. 4) is simple in design, and has a capacity of about 1 cu. ft. (0.028 cu. m.). It is not used as a source of air, but rather as a means for steadying the pressure in the apparatus. During a measurement the weights on the bell of the gasometer are adjusted so that it is slowly rising. This prevents the moist air in the gasometer from entering the rest of the apparatus.

The pressure gauge is an Ellison draft gauge with a scale graduated in millimeters, each of these divisions representing a pressure difference of 0.1 mm. of water.

The assembled apparatus (see Fig. 4) is arranged so that a stream of air from the compressed air line is steadied by means of the gasometer, passes through one or other of the flowmeters to the bottom of the mercury trough, and escapes through specimen *B*. The specimen is clamped on the felt gasket in the trough and surrounded on four sides with mercury from the mercury reservoir. The pressure gauge indicates the difference between the atmospheric pressure and the pressure under the specimen. At the lowest points in the tubes leading from the flowmeters and pressure gauge to the bottom of the trough, branch tubes, which dip into a small cup of mercury *E*, are inserted. This prevents any mercury which happens to leak through the specimens from blocking the tubes.

21. *Calibration.*—The flowmeters were designed to measure air flow rates of from 0.3 to 30 cc. per sec. to within 1 per cent. The capillaries were selected by trial, using rubber tube connections. The finished flowmeters were calibrated at a known temperature against a gasometer (1 rev. = 0.1 cu. ft. = 0.0028 cu. m.), which was in turn calibrated against a standard tenth-of-a-cubic-foot from the U. S. Bureau of Standards. Further tests showed that the readings of the flowmeters were practically independent of the discharge pressures and that, consequently, the variations of the atmospheric pressure would not sensibly affect their accuracy.

The coefficient of expansion of the gauge oil used in the manometers was calculated from the results of pycnometer measurements and the calibration data corrected to 25 deg. C. Charts were then made by means of which the manometer readings could be converted to air flow rates in cc. per sec.

The pressure gauge was calibrated at a known temperature by direct comparison with a Wahlen* gauge. The readings were then corrected to 25 deg. C.

Since the same oil was used in both the flowmeters and the pressure gauge, and since they were both calibrated to read correctly at 25 deg. C., no appreciable errors due to changes in the density of the oil would be introduced if the apparatus were used at other temperatures, provided the temperatures of the flowmeters and the pressure gauge were equal. This is due to the fact that the permeability of a brick can be considered constant for *small* changes in pressure and, consequently, errors in the flowmeter readings due to temperature changes are almost exactly balanced by similar errors in the readings of the pressure gauge.

---

*"The Wahlen Gage," Eng. Expt. Sta., Mar. 1921.

22. *Operation.*—The specimen is examined for large cracks leading from a $2\frac{1}{2}$-in.-wide face to a $4\frac{1}{2}$-in.-wide face. If any are present, they are waxed over on the $2\frac{1}{2}$-in. face to prevent mercury leaking through the brick when it is being measured. The brick is then placed on the felt gasket in the mercury trough and clamped down by means of C clamps. Mercury is forced from the reservoir into the trough until its surface is level with the upper surface of the brick. The stream of air from the compressed air line and the weights on the gasometer bell are adjusted until the pressure gauge indicates a pressure drop of 1.00 cm. The flowmeter with the greater capacity is tried first. If the reading of the manometer is too small to be made with accuracy, it is disconnected and the other flowmeter used. Readings are then made at intervals of one minute until constant readings are obtained. With ordinary firebrick equilibrium of flow is obtained in 2 or 3 minutes. The apparatus is then opened to the air and the mercury allowed to flow back to the reservoir, the brick is removed from the trough and its dimensions measured to the nearest thirty-second of an inch.

23. *Calculation of Results.*—The final reading of the flowmeter is converted to an air flow rate in cc. per sec. by means of the calibration chart. If only rough figures are wanted (within 10 per cent) this value can be used directly as the permeability of the specimen. For greater accuracy, corrections should be applied for the differences between the dimensions of the specimen and those of a standard straight brick (9 in. x $4\frac{1}{2}$ in. x $2\frac{1}{2}$ in). Experiments have shown that these corrections can be made with sufficient accuracy by assuming that the permeability of a brick varies directly as its cross-sectional area and inversely as its thickness. In applying these corrections, the following formula can be used:

$$P = \frac{16.2TP'}{A}$$

where P is the corrected permeability, P' the uncorrected permeability, T the thickness of the specimen in inches, A the cross-sectional area of the specimen in square inches, and 16.2 the ratio between the cross-sectional area and thickness of a brick of standard dimensions.

Other experiments have shown that the effect of the felt gasket and clamps is negligible and that the value of P, as obtained, will be correct to within 1 per cent with ordinary firebrick.

In many cases the corrections are unnecessary as the range of permeability of refractories is so great. For example, an accuracy of 10 per cent in determinations of permeability is sufficient for dividing the range from 30 cc. per sec. to 0.3 cc. per sec. into 48 differentiable divisions.*

24. *Precautions.*—It is very important that there be no air leaks between the flowmeter and the mercury trough. For this reason, all the connections are waxed and the apparatus is periodically tested for leaks by finding out if it will hold a slight pressure when a specimen of zero permeability, such as a firebrick coated with wax, is used, or when sufficient mercury to cover the specimen completely is forced into the trough from the reservoir.

25. *Modifications of Apparatus.*—By modifying the apparatus, materials much less permeable than firebrick can be measured. Such a modification is illustrated by the permeameter shown in Fig. 5, which is used in measuring the permeability of unburned clay brick, and covers the range from 0.01 cc. per sec. to 0.20 cc. per sec., using the standard pressure drop of 1 cm. water.

Besides being more compact in structure, this permeameter differs from the one described in the preceding paragraphs in having a flowmeter with a much finer capillary tube, drying tubes arranged so that dry air can be used in the measurements, and a counterpoised movable mercury reservoir.

The flowmeter was calibrated by connecting it to the top of a bottle of large diameter which was nearly full of water. The water was allowed to run from the bottle through a fine orifice into a small beaker. The rate of efflux of the water was obtained by weighing the beaker at definite intervals and was practically constant, since the change of water head in the large bottle was practically negligible. If the bottle was nearly full and the readings were taken over a considerable length of time, equilibrium of flow, i. e., constant flowmeter readings, would be secured, and the rate of efflux of the water could be taken as equal to the rate of air flow through the flowmeter.

---

*Calculated from the formula $N = \frac{\log a - \log b}{\log (1 + X/100)}$ where N is the number of divisions, a the upper limit of the range, b the lower limit, and X the percent accuracy.

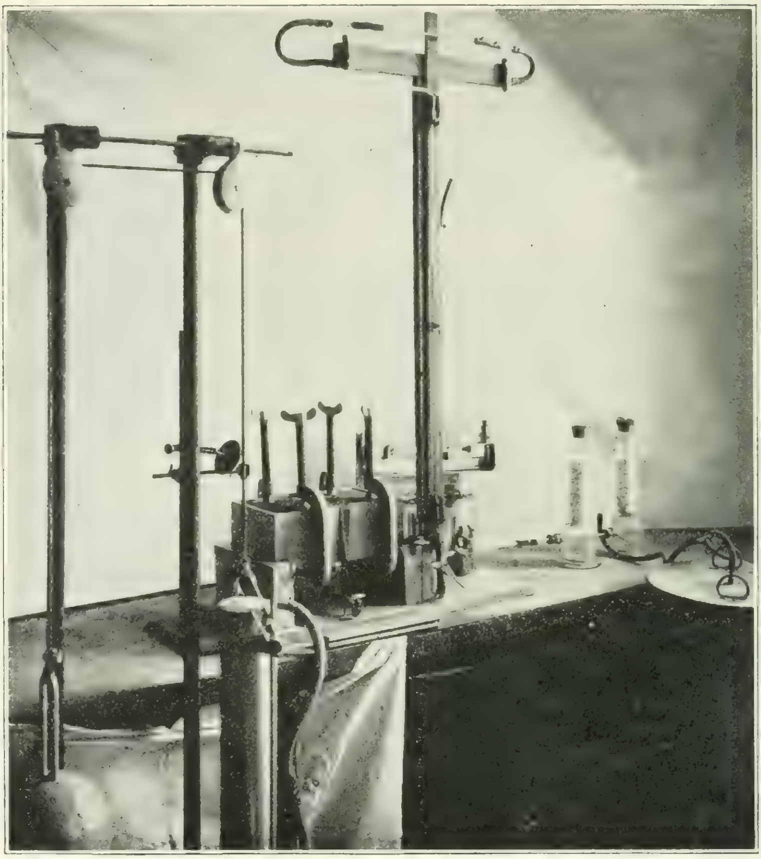

Fig. 5. Modification of Type B Permeameter

When working with unburned clay brick it was found necessary to control the moisture content of the specimens and of the air used in the measurements. The brick were dried to a constant weight at a definite temperature (100 deg. C.) and cooled in desiccators. Dry air was used in the measurements.

Since unburned brick are relatively impermeable, the rate of air flow in a measurement was very small and, consequently, the time required to reach equilibrium of flow was correspondingly great (from 10 to 20 min.).

For materials less permeable than unburned clay brick, the use of this type of permeameter would involve extremely long periods of time to obtain equilibrium of flow, unless the dimensions of the specimen and the standard pressure drop were changed. These latter modifications are limited because, ordinarily, bricks are the largest specimens available, and the standard pressure drop must be less than the pressure exerted by the mercury seal around the specimen.

The upper limit of service of type B permeameter has not been established. Permeabilities as high as 300 cc. per sec. have been measured by using mercury in the manometers of the flowmeters. The upper limit would be reached with air velocities so great that the formation of jets would interfere with the measurements.

APPENDIX A

1. *The Permeability of Typical Ceramic Bodies.*—The permeameters which have been described in the preceding sections have been used by the authors to measure the permeability of many different types of ceramic bodies. The results of some of these measurements are reported in Table 1. Each value represents an average of determinations on from 8 to 10 samples.

The values given in column 5 of this table are the permeabilities of the different bodies, expressed, in the cases where type A permeameter was used, in cubic centimeters of air per minute (measured at 560 mm. mercury) flowing through one square centimeter of a specimen 5 mm. thick under a pressure difference of 20 cm. of mercury, and, in the cases in which a permeameter of type B was used, in cc. per sec. through the thickness (2½ in. = 6.35 cm.) of a standard straight brick under a pressure head of 1 cm. of water (see sections 13 and 23).

In order to make a rough comparison of the permeability of the bodies measured by different methods, the results of all the measurements were calculated to a common basis of cc. per sec. per cm. cube per cm. of water pressure head, assuming that the permeability of the specimens was directly proportional to the pressure and the cross-sectional area, and inversely proportional to the thickness. The values so obtained are reported in column 6 of the table. While these calculations involve very doubtful extrapolations, the values obtained have sufficient significance to show the great differences that may exist between different ceramic bodies.

2. *Suggested Uses for Permeability Measurements.*—Some of the ways in which permeability measurements can be used to advantage in ceramic investigations will be briefly pointed out in the following paragraphs.

In the measurement of the thermal conductivity of refractories, there is always some question as to the amount of heat that is carried by the passage of gases through the specimen. This uncertainty often prevents an accurate comparison of the results of different experimenters. If, in future work, the permeability of the specimens were measured and the gas pressures in the apparatus noted, the magnitude of the heat flow due to the passage of gases through the specimen could be calculated and this uncertainty avoided.

TABLE 1.

THE PERMEABILITY OF TYPICAL CERAMIC BODIES

(1) Type of Body	(2) Raw Materials	(3) Type of Permeameter	(4) Method of Manufacture	(5) Standard Permeability	(6) Comparative Permeability
Raw clay bodies	Dorset English ball clay A	A	S. M.	0.29	1.2×10^{-5}
	No. 25 washed English ball clay	A	S. M.	0.36	1.5×10^{-5}
	English ball clay	A	S. M.	0.37	1.6×10^{-5}
	M. and M. Ivory-fat clay	A	S. M.	0.38	1.6×10^{-5}
	M. and M. English ball clay	A	S. M.	0.41	1.7×10^{-5}
	Washed clay	A	S. M.	0.42	1.8×10^{-5}
	Kentucky ball clay	A	S. M.	0.45	1.9×10^{-5}
	Hercules ball clay	A	S. M.	0.50	2.1×10^{-5}
	Ball clay	A	S. M.	0.54	2.3×10^{-5}
	Kentucky No. 8 ball clay	A	S. M.	1.00	4.0×10^{-5}
	Jernigan ball clay	A	S. M.	1.13	4.7×10^{-5}
	S. G. P. ball clay	A	S. M.	1.45	6.0×10^{-5}
Unburned face brick	Shale (Streator, Ill.)	B*	S. M.	0.024	5.0×10^{-4}
	Shale (Decatur, Ill.)	B*	S. M.	0.025	6.0×10^{-4}
	Shale (Springfield, Ill.)	B*	S. M.	0.044	1.1×10^{-3}
	Shale (Danville, Ill.)	B*	S. M.	0.051	1.2×10^{-3}
Face brick burned to 800°C.	Shale (Decatur, Ill.)	B*	S. M.	0.055	1.3×10^{-3}
	Shale (Streator, Ill.)	B*	S. M.	0.074	1.8×10^{-3}
	Shale (Danville, Ill.)	B*	S. M.	0.082	2.0×10^{-3}
	Shale (Springfield, Ill.)	B*	S. M.	0.11	2.6×10^{-3}
Plaster mold	Potter's plaster of Paris	B	cast	0.11	2.6×10^{-3}

*Modification of Type B (Fig. 5).

S. M.—Stiff Mud.

TABLE 1.—(Concluded).

THE PERMEABILITY OF TYPICAL CERAMIC BODIES

(1) Type of Body	(2) Raw Materials	(3) Type of Permeameter	(4) Method of Manufacture	(5) Standard Permeability	(6) Comparative Permeability
Burned firebrick	Flint, semi-flint and plastic clays	B	S. D. P.	0.27	6.6×10^{-3}
	New Jersey plastic clay	B	H. M.	0.38	9.2×10^{-3}
	Semi-flint clay	B	S. M.	0.46	1.1×10^{-2}
	Flint and semi-flint clays	B	S. M.	0.49	1.2×10^{-2}
	Second grade semi-flint and plastic clays	B	S. M.	0.64	1.6×10^{-2}
	Plastic clay	B	S. M.	0.70	1.7×10^{-2}
	Semi-flint clay	B	S. M.	1.34	3.3×10^{-2}
	Cheltenham plastic clay	B	D. P.	2.01	4.9×10^{-2}
Burned firebrick	Flint and semi-flint clays	B	H. M.	2.85	6.9×10^{-2}
	Flint and plastic clays	B	H. M.	4.5	1.1×10^{-1}
	Flint and plastic clays	B	S. M.	5.4	1.3×10^{-1}
	Grog, flint and plastic clays	B	S. M.	5.7	1.4×10^{-1}
	Pennsylvania clay	B	D. P.	6.3	1.5×10^{-1}
	Second grade semi-flint and plastic clays	B	D. P.	7.6	1.9×10^{-1}
	Porous kaolin (insulating brick)	B	D. P.	12.0	2.9×10^{-1}
	Sillimanite and clay	B	H. M.	18.5	4.5×10^{-1}
	Silicon carbide (recrystallized)	B	D. P.	33.0	8.0×10^{-1}
	Clay and carbon (insulating brick)	B	D. P.	50	1.2

S. M.—stiff mud. D. P.—dry press. H. M.—hand mold. S. D. P.—semi-dry press.

In determining the slag-resisting properties of a refractory, the rate at which the slag penetrates the pores of the refractory is an important consideration. This rate is governed by the permeability of the brick, other factors being equal, and, consequently, permeability measurements should be of use in determining the slag-resisting properties of the brick.

The ability of fireclay brick to withstand spalling conditions (rapid temperature changes) is governed to a considerable extent by the internal structure of the brick. It would appear, therefore, that measurements of the permeability and the porosity of fireclay brick should be of interest in this connection.

In many investigations it is an advantage to be able to determine whether any cracks have formed in a specimen. This is true in investigations of safe drying rates, and in testing the refractory blocks used for lining glass tanks. As the permeability of a specimen is greatly increased by the formation of a crack, permeability measurements should be of use in these investigations.

As the permeability of a body is very much affected by changes in structure, a comparison of the uniformity of structure of bodies made by different processes can be obtained by measuring the permeability of a large number of specimens made by the processes in question. Such a comparison of the different methods of making refractories has recently been made, using type B permeameter, and has yielded interesting results.

3. *The Use of Type A Permeameter as a Porosimeter.*—Type A permeameter can be used as an air expansion porosimeter if volume V contained between point P_1 (Fig. 2) and some point on tube D, such as P_4, is measured accurately.

The vacuum pump is disconnected from the apparatus, a glass plate is sealed to B in place of the specimen, and stopcock K turned so that the apparatus is open to the air at W. Reservoir R is adjusted until the mercury column is at P_1. Stopcock K is then turned so that C and T are connected and W is closed. Reservoir R is lowered until the mercury surface in D is at P_4 and the difference in level of the mercury columns in D and R is noted.

The volume V_f (cc.) of the apparatus between P_1 and the glass plate can then be calculated from the formula

$$V_f = V\left(\frac{P_3}{h} - 1\right)$$

where V is the valume of the apparatus between P_1 and P_2 (cc), P_3 is the atmospheric pressure (cm.), and h is the final difference in level of the columns of mercury in D and R (cm).

If the operation is repeated with a specimen sealed to B and sealed from the atmosphere by means of mercury, the sum of volume V_f and the pore volume of the specimen can be determined just as V_f was determined. By subtracting the value of V_f from this sum, the pore volume of the specimen is obtained.

THE UNIVERSITY OF ILLINOIS

THE STATE UNIVERSITY

Urbana

DAVID KINLEY, Ph.D., LL.D., President

THE UNIVERSITY INCLUDES THE FOLLOWING DEPARTMENTS:

The Graduate School

The College of Liberal Arts and Sciences (Curricula: General with majors, in the Humanities and the Sciences; Chemistry and Chemical Engineering; Pre-legal, Pre-medical and Pre-dental; Journalism, Home Economics, Economic Entomology and Applied Optics)

The College of Commerce and Business Administration (Curricula: General Business, Banking and Finance, Insurance, Accountancy, Railway Administration, Railway Transportation, Industrial Administration, Foreign Commerce, Commercial Teachers, Trade and Civic Secretarial Service, Public Utilities, Commerce and Law)

The College of Engineering (Curricula: Architecture, Ceramics; Architectural, Ceramic, Civil, Electrical, Gas, General, Mechanical, Mining, Municipal and Sanitary, and Railway Engineering; Engineering Physics)

The College of Agriculture (Curricula: General Agriculture; Floriculture; Home Economics; Landscape Architecture; Smith-Hughes—in conjunction with the College of Education)

The College of Education (Curricula: Two year, prescribing junior standing for admission—General Education, Smith-Hughes Agriculture, Smith-Hughes Home Economics, Public School Music; Four year, admitting from the high school—Industrial Education, Athletic Coaching, Physical Education

The University High School is the practice school of the College of Education)

The School of Music (four-year curriculum)

The College of Law (Three-year and four-year curricula based on two years of college work)

The Library School (two-year curriculum for college graduates)

The College of Medicine (in Chicago)

The College of Dentistry (in Chicago)

The School of Pharmacy (in Chicago)

The Summer Session (eight weeks)

Experiment Stations and Scientific Bureaus: U. S. Agricultural Experiment Station; Engineering Experiment Station; State Natural History Survey; State Water Survey; State Geological Survey; Bureau of Educational Research.

The Library collections contain (May 1, 1926) 707,722 volumes and 154,911 pamphlets.

For catalogs and information address

THE REGISTRAR
Urbana, Illinois